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# IMPROVING REAL-TIME HYDROLOGIC SERVICES IN USA

# PART I: ENSEMBLE GENERATED PROBABILISTIC FORECASTS

by

John J. Ingram, Danny L. Fread and Lee W. Larson

Office of Hydrology, National Weather Service,
Silver Spring, Maryland

## 1. INTRODUCTION

Floods are the leading weather related hazard throughout the world. A review of the world's recent and prominent flooding events remind us that major floods will continue to occur and are devastating. Preparedness for these events can lead to saving lives and property. Within the United States of America (USA) alone, floods cause an average of $3.6 billion in damages and 139 lost lives annually; over 75 percent of the Presidential disaster declarations for the USA are in response to flooding events. It is therefore important to make the mitigation of this hazard a high-priority task.

The USA weather program has been providing river and flood forecasts for the public since 1890 (Stallings and Wenzel, 1995). This program is managed by the US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS). Within the NWS, each of its thirteen River Forecast Centers (RFCs) typically issue stage forecasts for only one, two and three days into the future at most forecast points and crest forecasts out to about one week for a few selected forecast points. These forecasts have been provided primarily for the protection of life and property in the vicinity of rivers. They have also been used for the assessment of extended drought scenarios. Droughts, while generally not life-threatening in the USA, have a serious impact on agriculture, ecosystems and water management, and the economy in general.

This paper, along with it's companion paper (Fread, et. al., 1998), describes an advanced real-time hydrologic forecasting procedure which provides more accurate forecasts with long-warning times. A significant feature of the system is its application of meteorologic and climate (months to seasonal) predictions for the improvement of real-time hydrologic forecasts. The described system was operationally demonstrated for the Des Moines River basin in March of 1997.

## 2. NEW HYDROLOGIC FORECASTING SERVICES

Many federal, public, and private sectors possess an interest in the economic and environmental management of the USA's rivers. These sectors are now insisting upon forecast products with short (hours, few days) to long (several days, months, seasons) lead times depicting levels of forecast uncertainties. To meet this need, the NWS intends to capitalize upon its modernization in remote sensing, data automation, computer upgrades, graphical displays and advanced hydrologic/hydrometeorologic modeling (Braatz, et. al., 1998 and Fread, 1998). Implementation of the NWS Advanced Hydrologic Prediction System (AHPS) meets this objective and has successfully been operationally demonstrated during the snowmelt/spring-runoff season of 1997 on the Des Moines River basin, Iowa, USA (NWS, 1997). This is the first phase towards the national implementation of AHPS. The Des Moines River basin was chosen for this first phase because of the devastating impacts of the "Great Flood of 1993" (NWS, 1994) which included severe flooding in the city of Des Moines, Iowa.

AHPS provides enhanced hydrologic forecast capabilities as it builds upon the National Weather Service River Forecast System (NWSRFS). NWSRFS is a collection of programs and databases that provide a complete modeling and forecasting environment for the NWS River Forecast Centers (RFCs). One significant portion of the NWSRFS is an ensemble generator commonly referred to as the Ensemble Streamflow Prediction (ESP) system (Day, 1985). ESP is used to produce an ensemble of possible streamflow hydrographs which can be analyzed using standard statistical techniques to generate forecasts. As a part of the NWS effort to modernize its hydrologic forecasting services, the ESP analysis and product generation capability of NWSRFS has been updated. And, a new program called the ESP Analysis and Display Program (ESPADP) has been developed so that forecasters may now use a Graphical User Interface to select products and review forecasts. With ESPADP, a wide variety of data may be analyzed in the ESPADP program, including: stage, flow and precipitation. Another data type that ESPADP can ingest and analyze is stage output from the FLDWAV operation in the NWSRFS.

The AHPS implementation for the Des Moines River basin began in 1995. AHPS functionality and associated implementation activities include:

- Provide advanced hydrometeorologic/hydrologic modeling procedures that better account for the natural and man-made complexities of the nation's river basins;

- Implement the NWS Ensemble Streamflow Prediction (ESP) procedure (Day, 1985) in order to provide probabilistic hydrologic forecasts into the future from days to months;

- Couple meteorologic forecasts and climate predictions within the ESP procedure;

- Include the effect of reservoir operations in both short-term and long-term forecasts;

- Implement dynamic streamflow modeling in river reaches with significant dynamic effects caused by backwater, levee overtopping, or other transient phenomena; and,

• Provide advanced products (e.g., probability of occurrence information and inundated area mapping) for water resources management activities to other federal, state and local organizations.

These implementation activities were carried out by personnel of the NWS North Central River Forecast Center (NCRFC), Chanhassen, Minnesota; the Regional Hydrologist and other staff of the NWS Central Region Headquarters, Kansas City, Missouri; the Des Moines Weather Service Forecast Office (WSFO), Johnston, Iowa; and the NWS Office of Hydrology, Silver Spring, Maryland. The design and evaluation of the AHPS hydrologic forecast products involved the participation of NWS customers.

In order to provide useful AHPS products during the Des Moines demonstration, the NWS met with representatives from other federal, state and local water facility management and emergency management agencies during October 1996. Through this joint activity, the NWS and its hydrologic forecast customers of the Des Moines River basin arrived at specific goals for the AHPS March 1997 demonstration: 1) use Quantitative Precipitation Forecasts (QPF) in the short-term forecasts, 2) use climate coupling and ESP techniques in long-range hydrologic products, 3) provide probability information in hydrologic products, and 4) demonstrate a flood inundation mapping capability. Additional conclusions from that meeting were:

- Internet would be the primary system for issuing AHPS products to users. The WSFO Des Moines home page (http://www.crh.noaa.gov/dmx) would incorporate the following AHPS products:

  -- A map of the Des Moines River basin showing all hydrologic forecast points including appropriate E-19 data (Figure 1). E-19 data provides the details at each location including flood stage, equipment, site history, and maps.

  -- Short-term products that would normally be 1- to 3-day river/flood forecasts with 24 hours of QPFs and displayed as a hydrograph.

  -- AHPS products, including the use of QPF and climate predictions (Figures 2 and 3) for 21 forecast locations in the Des Moines River basin include: ESP probability time series (weekly) for flow, volume, and stage out to 60 days; and, 60-day exceedance probability plots for flow and stage.

  -- A flood inundation map for the vicinity of Des Moines, Iowa (Fread, et. al., 1998)

  -- Miscellaneous graphics products including data such as precipitation totals and Flash Flood Guidance displays.

- AHPS products would be generated once per week, on Wednesdays, beginning with the first Wednesday in March (5th) and ending with the last Wednesday in March (26th).

- AHPS products would be in addition to the usual routine hydrologic products prepared by NCRFC such as flash flood guidance, river forecast, and extended streamflow guidance products.

- Verification of the AHPS demonstration would be based on a comparison of standard NCRFC procedures, ESP computations, and observed crests. Also included would be a summary of user evaluations as to the quality and usefulness of ESP-type products.

## 3. AHPS METHODOLOGY

### 3.1 Computation of Forecasts

Forecasts distributed during the AHPS demonstration in Des Moines, Iowa, were computed using a variation to the standard ESP technique (Day, 1985). The standard ESP technique is part of the NWS operational flood forecasting system called the NWS River Forecast System (NWSRFS). The ESP technique used within the AHPS demonstration utilized QPFs and climate predictions; referred to as climate coupling.

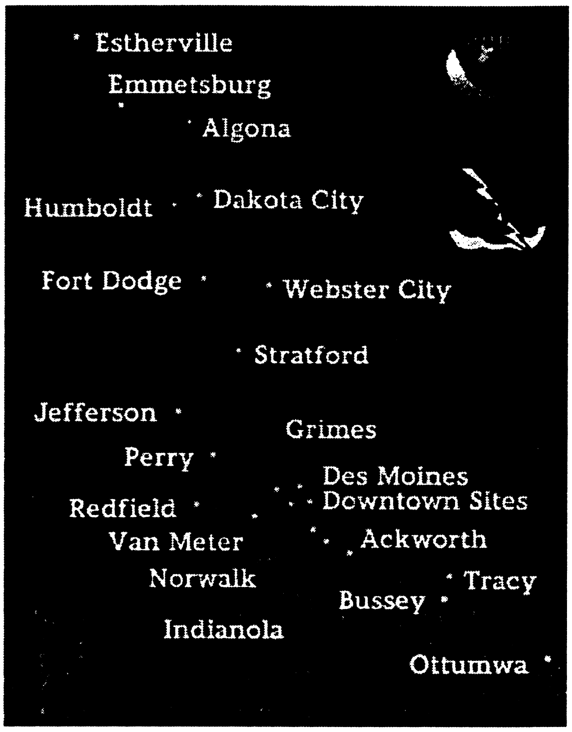

Figure 1. Des Moines River basin as found on the WSFO Des Moines homepage.

To forecast with the ESP technique, an ensemble of possible streamflow hydrographs are calculated by initializing hydrologic models with the current states of the hydrologic system and then calculating hydrographs with those models using historical precipitation and temperature time series. A distribution is then fit to a sample taken from this ensemble of streamflow hydrographs for a specified future time period. The fitted distribution describes the likelihood of an event occurring during the specified period of time. It is from this fitted distribution that forecast products are derived. An empirical distribution was used as the underlying distribution for all the AHPS demonstration forecasts.

An alternate method for calculating the ensemble of streamflow forecast was developed for the demonstration. This method integrates long-range meteorological forecasts and climate predictions into the streamflow forecasts. The method consists of adjusting historical mean-areal precipitation and temperature time series relative to current meteorological outputs/ climate outlooks prior to using them as input to the hydrologic models (Perica, 1998). The adjustment is based on the comparison of coinciding marginal exceedence probabilities of historical records and climate outlooks. The daily adjustment coefficients, $\lambda$, were calculated from the 2- to 6-day NWS Hydrometeorological Prediction Center precipitation and temperature forecasts, the 7- to 11-day NWS Climate Prediction Center (CPC) precipitation and temperature forecasts, the 1-month climate outlook from CPC, and the seasonal climate outlooks from CPC. The Des Moines WSFO produced the 24-hour QPFs that were also blended into the ESP forecasts.

### 3.2 Description of Forecast Products

In order to convey model output and information to users it was necessary to develop the ESP Analysis and Display Program (ESPADP). Two enhancements resulted from ESPADP: 1) a model analysis procedure and product generator leading to greater abilities to present probabilistic products for water resource managers, and 2) the provision of interactive graphical displays for both hydrologic forecasters and users to maximize their ability to understand and interpret ESP output.

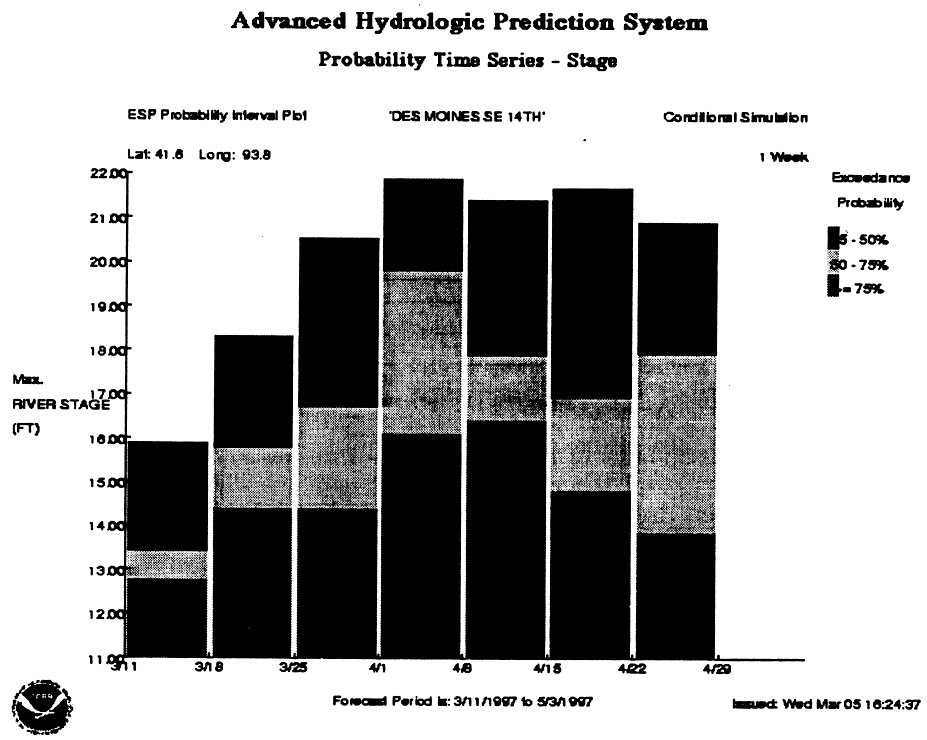


Figure 2. ESP probability interval plot of stage exceedance for seven weekly time intervals.

Hydrologic products have typically been tabular in nature and limited to short time frames. These new AHPS graphical products are able to pass on greater amounts of data and information for longer periods of time. Examples of these displays are shown in Figures 2 and 3, the ESP Probability Interval Plot and the ESP Exceedance Plot respectively. The need for such products has been voiced by water resource managers after all major flood disasters since the Great Flood of 1993. A description of these and other AHPS demonstration products follow:

Probability Interval Plots for Maximum Flow, Maximum Stage, and Total Volume of Flow. These plots show the probability that the maximum flow (cubic feet per second), maximum stage (feet, Figure 2), and total volume of flow (acre feet) at a point on a river will exceed a particular value in a 7-day period. The vertical axis shows measured unit and the horizontal axis shows time. Each vertical bar represents the probabilities for a 7-day period. The three probability levels are: greater than 75 percent, 75-50 percent, and 50-25 percent.

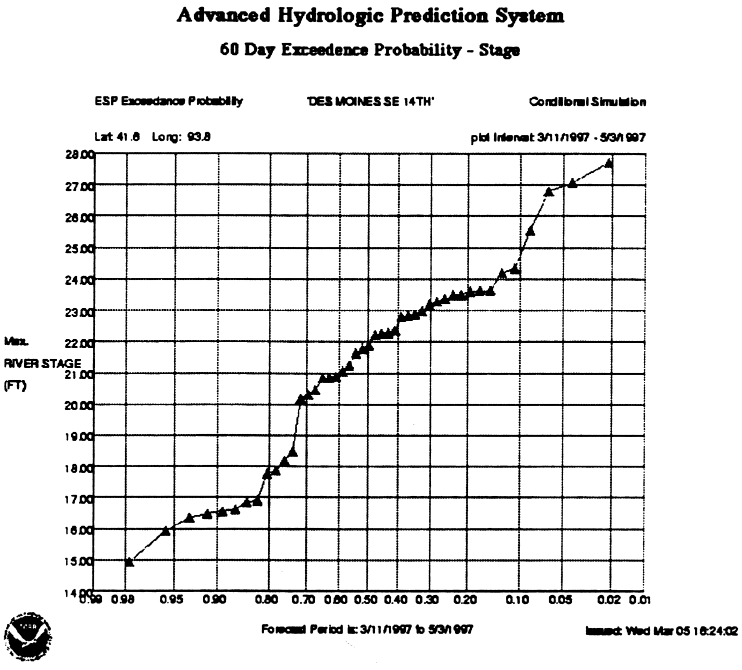


Figure 3. ESPADP generated probability of crest exceedance for a 60 day forecast period.

60-day Exceedance Plots for Maximum Flow and Maximum Stage. These plots shows the probability distribution for the maximum flow (cubic feet per second) and maximum stage (feet, Figure 3) over the identified 60-day period. The vertical axis shows the measured unit and the horizontal axis shows the probabilities. The triangles indicate sample points, and the line through the points represents the distribution that has been fit to those sample points. A point on the line indicates the probability that a specific flow, or stage, will be exceeded some time during the identified 60-day period.

Inundation Map for Maximum Stage. The AHPS Flood Inundation Map demonstrated the capability of generating real-time inundation maps derived from NWS hydrologic forecasts. . Benefits derived from real-time inundation mapping and future advancements are presented in the companion paper (Fread, et. al., 1998). The inundation map depicts the probabilities that specific areas around the city of Des Moines, Iowa will be flooded during the identified 60-day period. Any given area is assigned one probability range for the specific 60-day period: a greater than 75 percent chance of flooding; a 50-75 percent chance of flooding; a 25-50 percent chance of flooding; or a less than 25 percent chance of flooding. The map does not give information about flood depth above the ground, river stage, or flood return interval and is not related to any hypothetical 25-, 50-, or 75-year return-interval flood. The inundation map is based on the best digital elevation model (DEM) data available. If a DEM of greater resolution and accuracy were available, it could be used with the demonstration software and procedures to produce a more accurate flood inundation map based on the NWS hydrologic forecasts.

## 4. AHPS DEMONSTRATION RESULTS

During the March 1997 AHPS demonstration, only a few minor flood events occurred. Of nine forecast locations that rose slightly above flood stage, three were due to backwater due to ice jams. Furthermore, a snowmelt period had occurred prior to March and therefore had minimized the possibilities for product evaluation. At any rate, from the perspective of demonstrating AHPS procedures, software, and implementation the success of the demonstration was achieved.

In general, it was found that the probability interval plots for observed maximum stages for each week were distributed nearly the same for the intervals of 25-50 percent and 50-75 percent, 36 and 37 cases out of 84 respectively. Eleven cases fell in the interval less than 25 percent and no cases were noted in the interval greater than 75 percent. It was also noted that at some locations the timing of the observed maximum stage occurred in the maximum week of the probability interval plot. These findings were realistic and are expected results.

Figure 4 provides a comparison of forecasts with observed crests using the exceedance probability plot for each location. The outlook numbers (future potential stage values assessed via traditional NWS approaches) were determined on February 27, 1997. The AHPS conditional exceedence probabilities were taken from the March 5, 1997 release. The observed crests generally occurred within a month or less of the AHPS release date. Outlook A is the potential crest for existing conditions only while Outlook B corresponds to the potential crest for existing conditions plus future climate precipitation. (Locations on the Des Moines River are: JCKM5, Jackson, Minnesota; ESVI4, Estherville, Iowa; EMTI4, Emmetsburg, Iowa; HBTI4, Humbolt, Iowa; FODI4, Fort Dodge, Iowa and STRI4, Stratford, Iowa.)

The data of Figure 4 indicate that the traditional outlook products (A and B) tend to encompass a wide variety of conditions and contain some degree of subjectivity, as indicated by the range of probabilities between Outlooks A and B. The AHPS products provided information over a broad range of stages, but it is as yet undetermined how a user could arrive at a best single forecast number as "most likely," if that is what is desired. It is encouraging to note, however, that in most cases (Figure 4), the 50 percent exceedance probability stage was as close or closer to the final observed crest than either Outlook A or B. Since the demonstration was limited to 1 month, verification data is limited; additional data for future events should be gathered and examined.

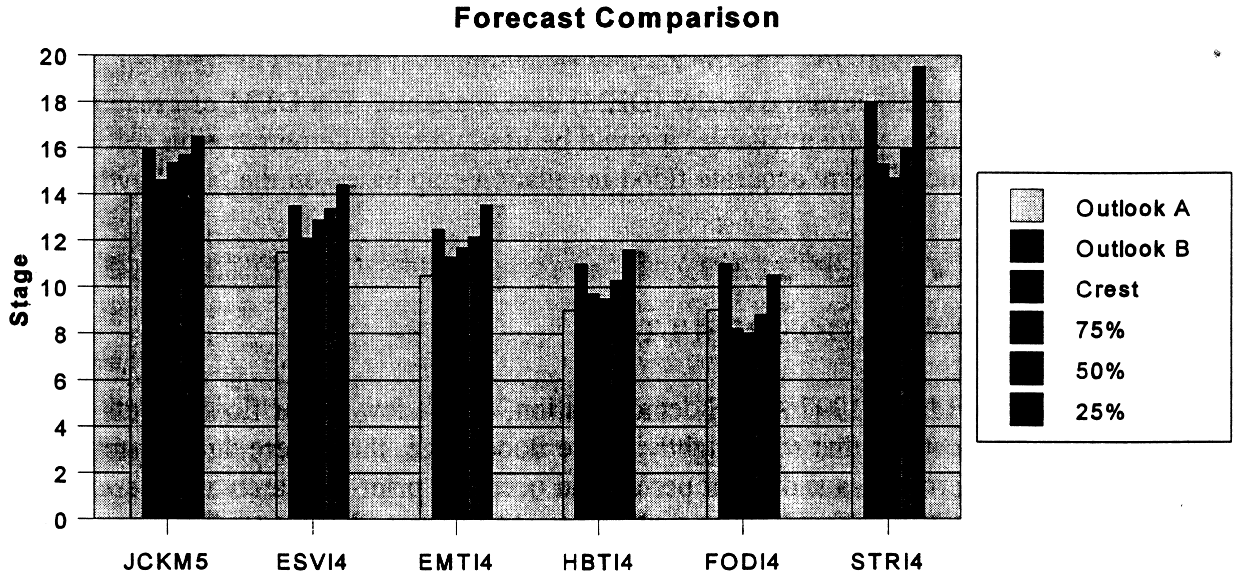


Figure 4. Comparison of forecasts to observed crests.

## 5. OBSERVATIONS AND RECOMMENDATIONS

The AHPS demonstration was very successful in that all major implementation goals were met and demonstrated. However, as an initial effort, there were areas where improvements can be made. Some observations and recommendations follow:

- ESP spring flood outlook values, particularly at the 50 percent probability of exceedance level, compared well to traditional forecast techniques in areas where snowmelt flooding occurred. Furthermore, these AHPS products gave significantly more information to the users.

- Users of AHPS products, both external to and within the NWS, generally said the new product formats were very useful and contained additional information. Lack of flooding activity during the demonstration reduced interest by some users, especially external users.

- Inundation mapping was successfully demonstrated for the city of Des Moines, Iowa (Fread, et. al., 1998). Again, lack of flooding events during the demonstration minimized usefulness of this product to the users. A problem in this area is the lack of sufficiently accurate digital elevation data sets for use in generating the maps. Creating such data sets over large areas could be difficult.

- The use of an Internet home page for outside user access of AHPS products was very successful. The home page at WSFO Des Moines is still in use and can be accessed at:

http://www.crh.noaa.gov/dmx/ahps

This concept opens up an entirely new and easy access of NWS products by users.

- The use of QPF and climate products (1- to 5-day, 6- to 10-day, 30-day, and seasonal) were all successfully demonstrated. The ESPADP-generated forecast products (stage, flow, and volume) out to 60 days was demonstrated as viable and potentially extremely useful.

- Consideration should be given to linking the conditional exceedance probability graphs with flood frequency curves from flood insurance studies. This would provide additional helpful information for external users in a format with which they may be more familiar.

- Staff time required to create the AHPS suite of products is an issue of concern. The time required to generate the daily forecast products averaged 1 hour; more during active conditions. The time required to generate and issue the AHPS ESP products averaged 4.5 hours. This relates to both staff and system (computer) resources. Techniques should be reviewed and revised to reduce runtime and staff time. Experience and optimization should reduce this concern significantly.

- Additional training resources need to be developed for the interpretation and understanding of the statistical products and procedures. There were occasions when users misunderstood the various AHPS products. Also, it would be interesting for operators of similar systems to learn of possible misinterpretations of probabilistic forecasts.

## 6. AHPS FUTURE

The AHPS continues to run at NCRFC and is available to the public via the NWSFO Des Moines home page. It presently runs once per month in conjunction with CPC updates, but would be updated more often as the hydrologic situation in the Des Moines basin dictates. It is recognized that additional operational verification data must be developed and analyzed.

The demonstration clearly showed the benefits of AHPS-type products and highlights the requirement for national implementation of AHPS. At present, a slow implementation of AHPS over several additional basins in the North Central USA is anticipated. Possible deployment in the Pacific Northwest, the Colorado River in Texas, and the Susquehanna basin in Pennsylvania is also anticipated. However, widespread major deployment of AHPS across the entire country must await additional funding.

## 7. CONCLUSIONS

The most significant aspect of the demonstration was user response to AHPS. On a scale of 1 to 10, NWS staff rated the quality and usefulness of AHPS as 8. All the AHPS products were evaluated as being "useful" to "essential" for NWS operations. NWS staff cited the probabilistic forecasts, graphical output, and consolidation of hydrologic information as the things they liked best about AHPS. External users rated AHPS products as 7 or 8 (on a scale of 1 to 10). The external users evaluated most AHPS products as "essential" to their operations. The external users stated that what they especially liked about AHPS was "the information was right before you and then you could plan your strategies."

Overall, the March 1997 demonstration successfully met the implementation goals to demonstrate an operational long-term probabilistic forecast system. Furthermore, the demonstration revealed that AHPS is mature enough for implementation in other regions of the nation. It's largely now the economic benefits from the introduction of probabilistic river forecasts which are driving AHPS towards national implementation.

As AHPS is implemented, it will provide a multitude of water resource managers with reliable hydrologic data and understandable displays which are utilized in the decision making process for the economic and environmental well-being of the USA's water resources. AHPS greatly improves and enhances NOAA's capability to provide more reliable, long lead-time and accurate forecasts to meet these priorities. And, NOAA's customers, becoming better informed and equipped, will be in a stronger position to meet their objectives. As a result, floodplain and water resource management decisions will become more confidently determined than previously possible. Thereby, as these advanced products come on line, the implementation of AHPS will elevate NOAA's leadership role in fostering economic gains for environmentally sound decision making for all streamflow regimes and climatic scenarios.

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